Tokamak fusion, does it have a path ?

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Presented at Physics Colloquium

Princeton Univercity

December 07, 2000, Princeton, NJ

[1] **This work is supported by US DoE contract No. DE–AC020–76–CHO–3073.**

Abstract

Tokamak fusion devices, which for 3 decades were leaders in the World fusion program and which made a leap from 1 keV plasma temperature in Russian T-3 machine (1968) to 40 keV and 10.7 MW of DT fusion power in TFTR at PPPL (1994), are now in an eventual state of defeat and possible shutdown in the US. Despite much better understanding of the tokamak plasma now, many fundamental problems on the way to the tokamak-reactor remain unresolved even at the conceptual level. These problems include stability and steady state plasma regime control, power extraction from both the plasma and the neutron zone, activation and structural integrity of the machine under 14 MeV fusion neutron bombardment, maintenance of future reactors, etc.

This presentation describes the physics of a recently (Dec., 1998) invented method of magnetic propulsion for driving liquid metal streams in the tokamak magnetic field. This effect in combination with the idea of renewable and absorbing walls at the plasma boundary (which previously was only a theoretical abstraction) leads to breaking with the conventional approach to the tokamak fusion reactor. The resulting new ideas, which in many aspects rely on the best US tokamak experiments on TFTR (PPPL) and DIII-D (GA, San Diego) and basic theory, raise the hope on a new research path for tokamaks toward a practical fusion reactor.

OUTLINE

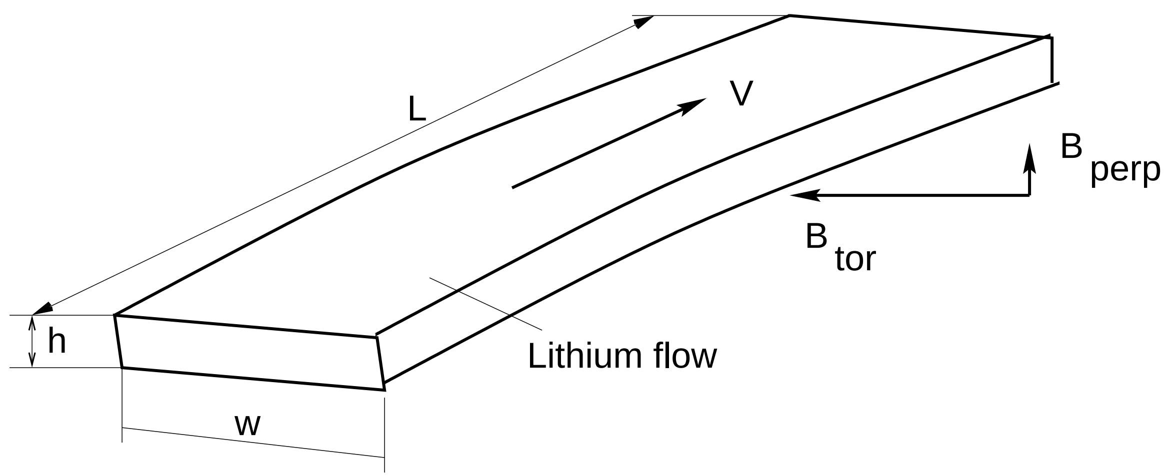
1. Magnetic propulsion of liquid lithium.
2. Lithium Walls and tokamak plasma.
   (a) LiWalls and energy extraction from the plasma;
   (b) LiWalls and plasma stability;
   (c) LiWalls and plasma energy confinement;
3. Yacht Sail approach for tokamak fusion reactors.
4. Summary.
5. Does tokamak fusion have a path ?

1 Magnetic propulsion of liquid lithium

Goto Cbpu code.

There 3 magnetic Reynolds numbers which control lithium MHD in tokamaks

$$\begin{aligned} \text{dynamics}: &\quad \Re_0 \equiv \mu_0 \sigma L V, \\ \text{electro-dynamics}: &\quad \Re_1 \equiv \mu_0 \sigma h V, \\ \text{dynamics}: &\quad \Re_2 \equiv \mu_0 \sigma \frac{h^2}{L} V, \\ &\quad \mu_0 \sigma \simeq 4 \ \left[\frac{sec}{m^2}\right]. \end{aligned} \tag{1.1}$$



Characteristic flow parameters:

$$\begin{aligned} V &= 20\ m/sec \rightarrow \rho\frac{V^2}{2} \simeq 1\ [atm], \\ B &= 1\ T \rightarrow \frac{B^2}{2\mu_0} = 4\ [atm], \\ B &= 5\ T \rightarrow \frac{B^2}{2\mu_0} = 100\ [atm]. \end{aligned} \tag{1.2}$$

Dynamic pressure losses are determined by $\Re_0$ and $\Re_2$

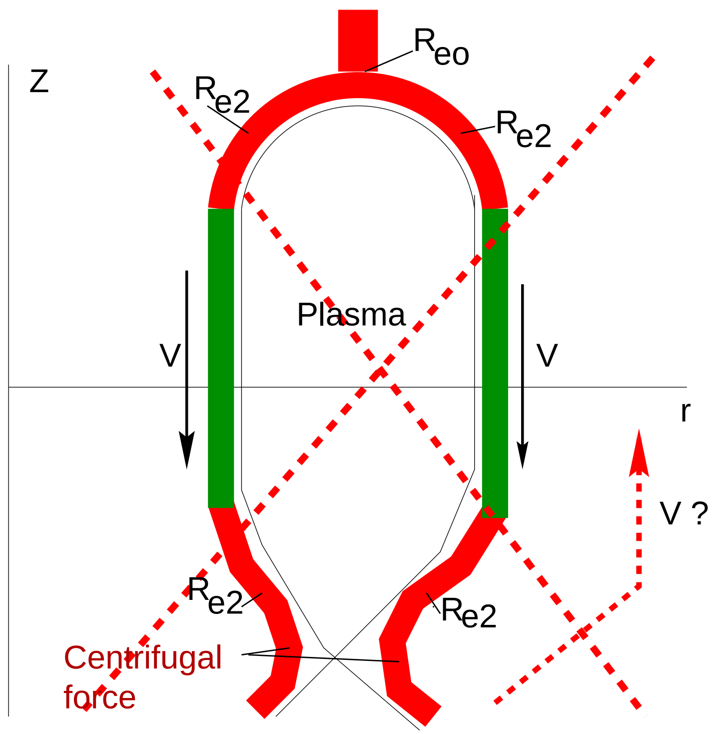
$$\begin{aligned} \Re_0 :\quad & \Delta\rho\frac{V^2}{2} = \mu_0\sigma L V\frac{B_\perp^2}{2\mu_0}, \\ \Re_2 :\quad & \Delta\rho\frac{V^2}{2} = \mu_0\sigma\frac{h^2}{L}V\Delta\frac{B_\parallel^2}{2\mu_0}, \\ & \mu_0\sigma \simeq 4\ \left[\frac{sec}{m^2}\right]. \end{aligned} \tag{1.3}$$

Magnetic fields from the currents in the stream are determined by $\Re_1$

$$\Re_1 :\quad B_{||out} - B_{||in} = \mu_0\sigma h V B_\perp. \tag{1.4}$$

Lithium “water-falls” will not flow through the tokamak strong toroidal field

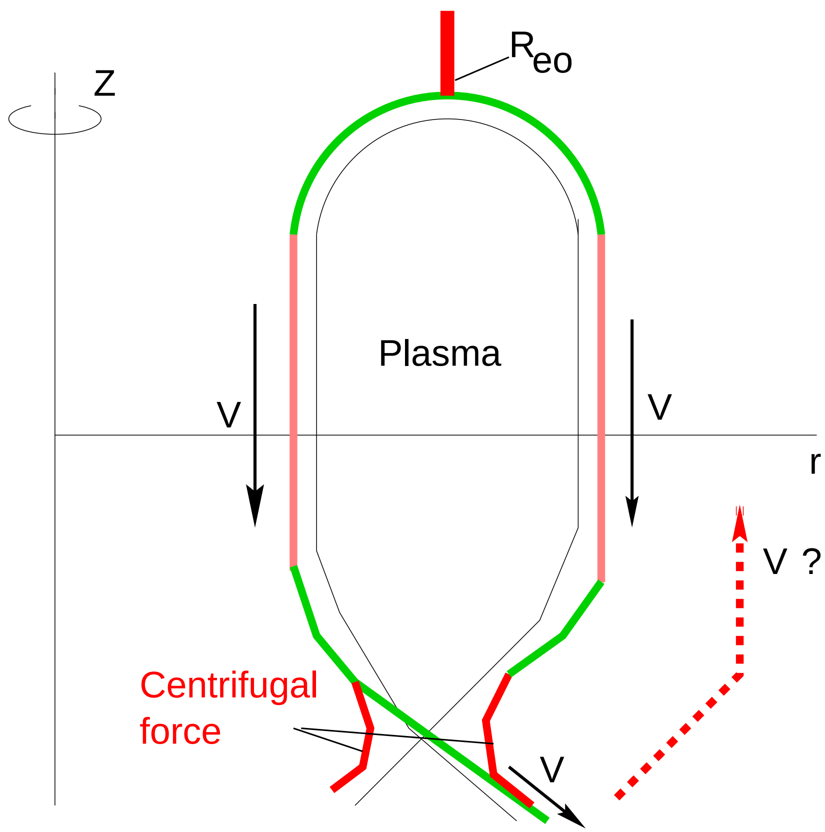
$$
\begin{aligned}
&h = 0.1\, m, \quad L_1 \simeq 0.2\, m, \quad L_2 \simeq 3\, m, \quad V > 2-5\, [m/sec],\\
&\Re_0 = 4 L_1 V => 1.6,\\
&\Re_2 = 4\frac{h^2}{L_2} V = 4\frac{h}{L_2}(hV) \simeq 0.01 - 0.025.
\end{aligned} \tag{1.5}
$$



$$
\boxed{\rho\frac{V^2}{2} \ll \Re_2 \Delta \frac{B_{tor}^2}{2\mu_0}}
$$

Momentum driven thin walls have many of unresolved problems in lithium MHD

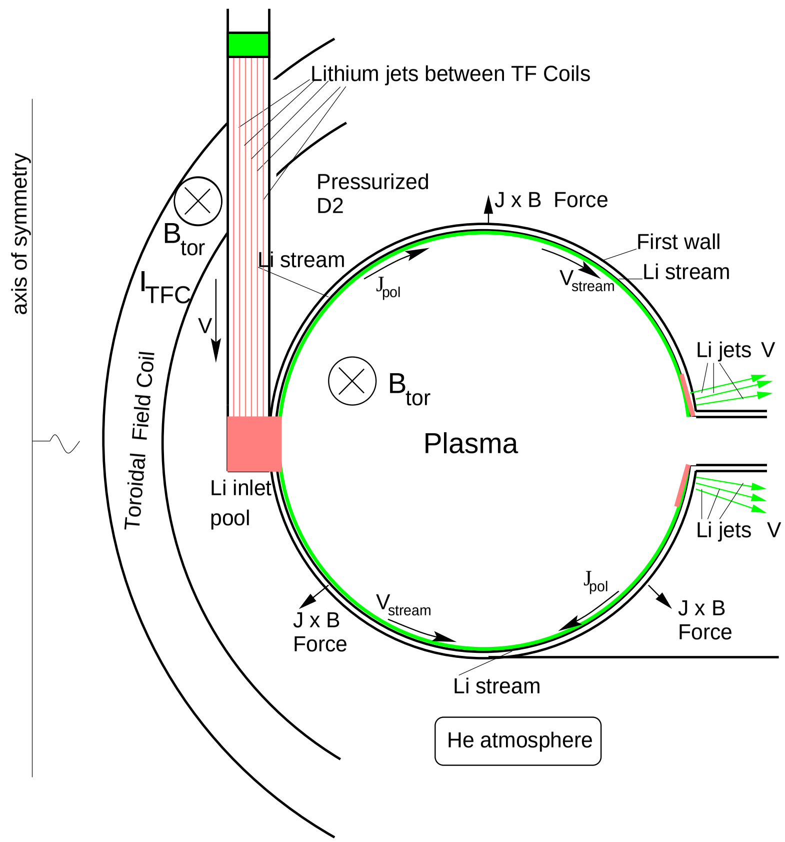
$$h = 0.01\ m, \quad L_1 \simeq 0.02\ m, \quad L_2 \simeq 3\ m, \quad V \simeq 20\ [m/sec],$$
$$\Re_2 = 4\frac{h^2}{L_2}V \simeq 1.3 \cdot 10^{-4}. \tag{1.6}$$



$$\boxed{\Re_0 = 1.6, \quad \rho\frac{V^2}{2} < \Re_0 \frac{B_{pol}^2}{2\mu_0}}$$

Magnetic propulsion opens the possibility for intense plasma facing lithium streams in tokamaks

$$p_{\mathbf{j}\times\mathbf{B}}\big|_{inlet} - p_{\mathbf{j}\times\mathbf{B}}\big|_{outlet} \gg \Re_2 \frac{B_{tor}^2}{2\mu_0}, \quad \Re_2 \equiv \mu_0 \sigma \frac{h^2}{R} V \simeq 0.0015$$



- Driving electro-magnetic pressure

$$p_{\mathbf{j}\times\mathbf{B}}\big|_{outlet} > 1\ atm$$

$$p_{\mathbf{j}\times\mathbf{B}}\big|_{inlet} - p_{\mathbf{j}\times\mathbf{B}}\big|_{outlet} \simeq 1.5 - 3\ [atm]$$

- Flow parameters

$$V \simeq 20\ m/sec, \quad h \simeq 0.01\ m$$

- Magnetic Reynolds numbers

$$\Re_1 \equiv \mu_0 \sigma h V \simeq 0.8, \quad \Re_2 \simeq 0.0015$$

- Stream are robustly stable due to centrifugal force

$$\rho \frac{\langle V^2 \rangle}{2} > \frac{a}{2R} p_{wall} n_r$$

2 Lithium Walls and tokamak plasma

Plasma facing surface is right at the critical place in the fusion reactor between the plasma and the neutron absorbing zone

Three things are the most important:

1. power and particle extraction;
2. effect on core confinement

$$n_{DT} \cdot T_{DT} \cdot \tau_E > 5 \times 10^{21}\ m^{-3} \cdot keV \cdot s, \quad n_{DT} \cdot T_{DT} \cdot \tau_E \propto \tau_E^2$$

3. effect on plasma stability.

$$Power_{fusion} \propto (n_{DT} \cdot T_{DT})^2 \propto \beta^2, \quad \beta \equiv \frac{2\mu_0 \langle 2nT \rangle}{B^2}$$

3 LiWalls and energy extraction from the plasma

Intense lithium streams have reactor relevant power extraction capabilities

$$\boxed{\Delta T_{max} = q_{wall}\sqrt{\frac{4t_{transit}}{\pi\kappa\rho c_p}}, \quad d_{skin} \equiv \sqrt{\frac{\kappa t_{transit}}{\rho c_p}}}$$

$$\boxed{R = 6\ m, \quad a = 1.6\ m, \quad q_{wall} \simeq 3.5\ \frac{MW}{m^2}, \quad P_{wall} = 4\pi^2 Ra q_{wall} \simeq 1.3 GW}$$

even with no reliance on the vortices in the streams.

Intense lithium streams can keep wall temperature low (250-300^o C) at the neutron wall loading $> 10\ MW/m^2$.

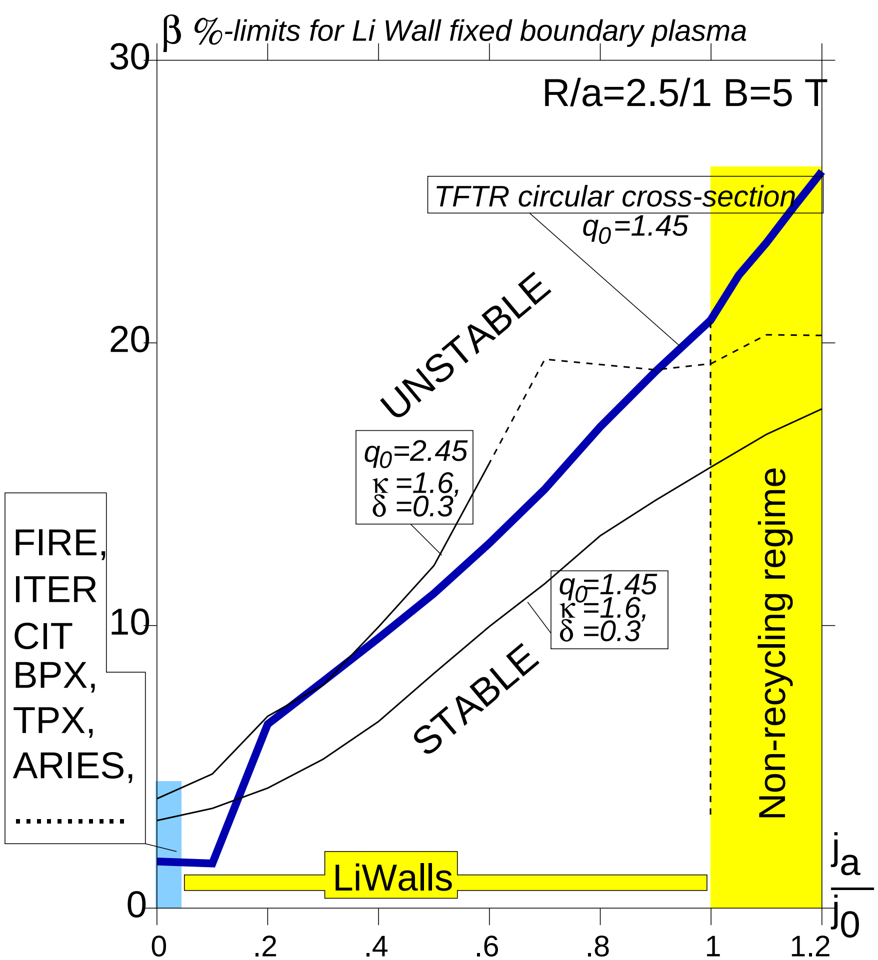
4 LiWalls and plasma stability

Intense lithium streams may create the best situation for the plasma stability control

$$Power_{fusion} \propto (n_{DT} \cdot T_{DT})^2$$

Goto Cbpu code.

Li walls allow much higher operational plasma pressures.



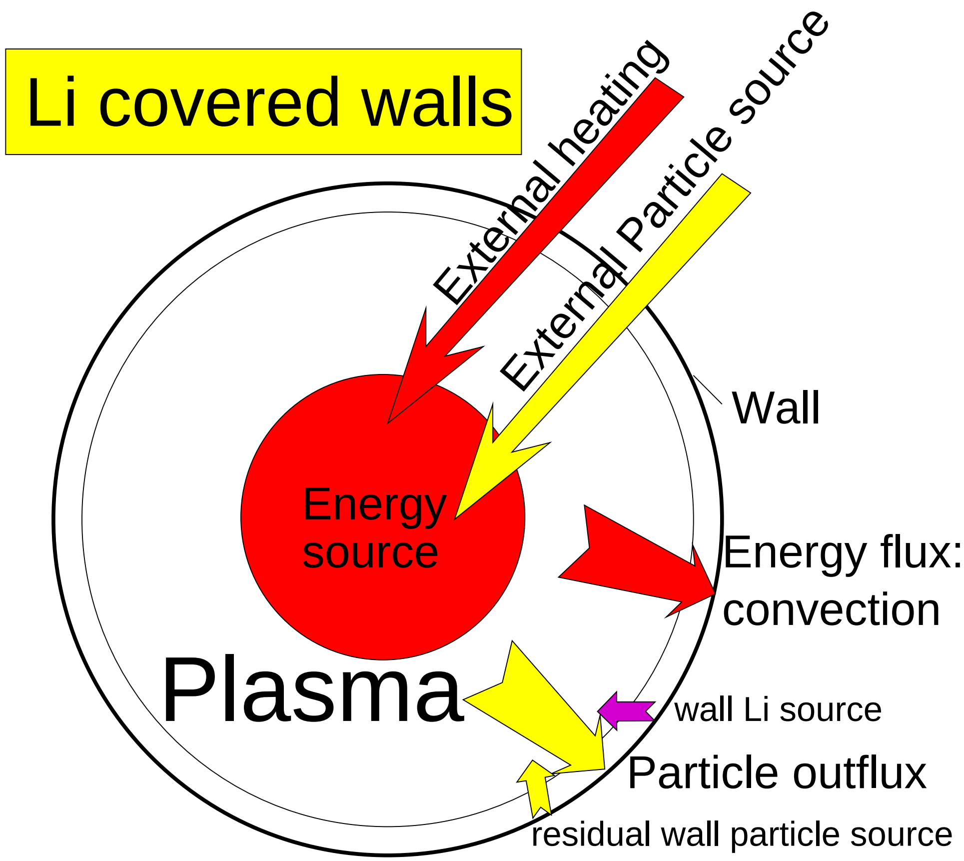
β - limits for the second stability regime

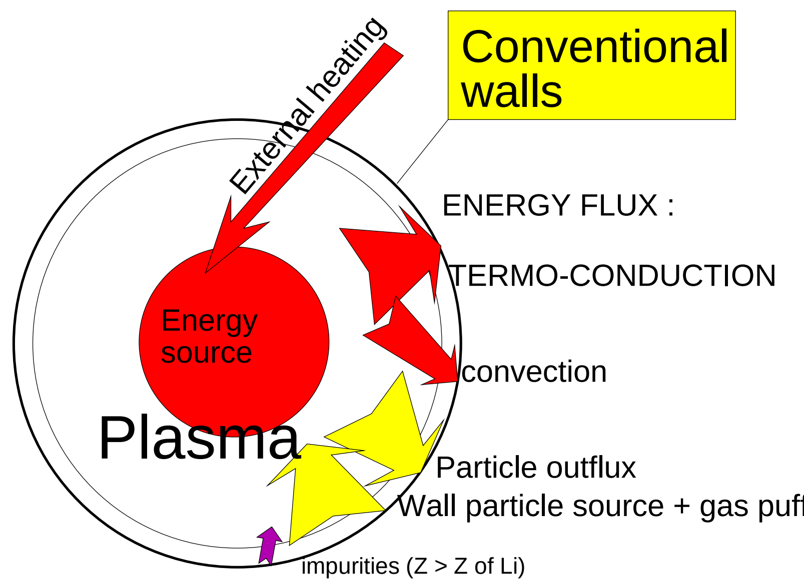
- fixed boundary plasma
- n=1,2,3 + ballooning modes (DCON,PEST-2,BALLON)
- current density with an edge pedestal

$$\mathbf{j}_{\parallel} = j_a + (j_0 - j_a)\left(1 - \frac{r^2}{a^2}\right)$$

5 LiWalls and plasma energy confinement

Li is an excellent getter for the hydrogen plasma particles.





Lithium can be propelled along the walls
for power and particle extraction.

Improved energy confinement is extremely for igniting the plasma

$$n_{DT} \cdot T_{DT} \cdot \tau_E > 5 \times 10^{21}\, m^{-3} \cdot keV \cdot s, \quad n_{DT} \cdot T_{DT} \cdot \tau_E \propto \tau_E^2$$

Plasma profiles are determined by the particle continuity equation

$$\Gamma \equiv Snv = const = (\Gamma)_a$$

and by the energy balance

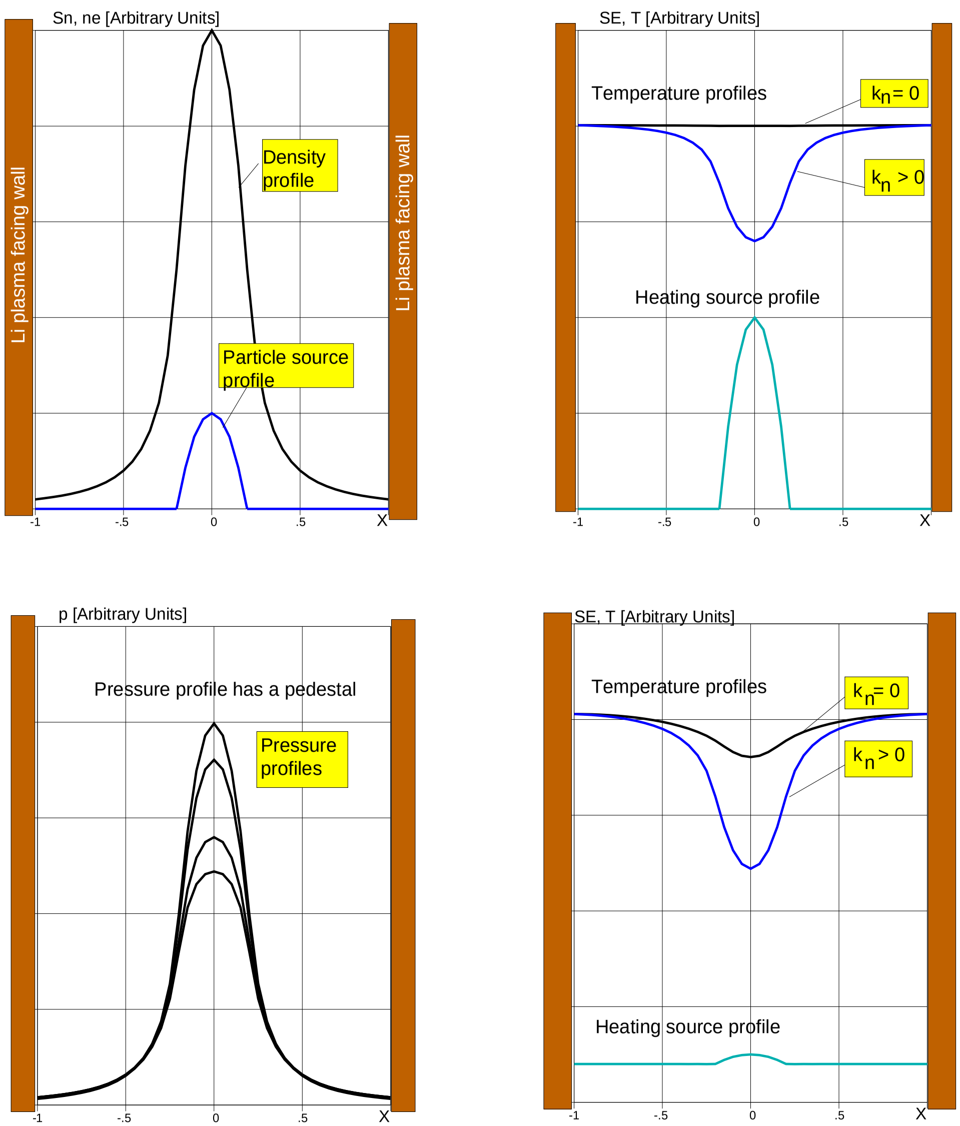
$$\frac{5}{2}\Gamma T - S(\kappa_T \nabla T + \kappa_n \nabla n) = \int_0^r P_E dv$$

With perfectly absorbing walls plasma does not know the temperature of the (cold) walls and leaves no room for thermo-conduction

$$\left(\frac{5}{2}\Gamma T\right)_{edge} = \int_0^a P_E dv, \quad T_{edge} = \frac{\int_0^a P_E dv}{\frac{5}{2}\Gamma} \quad P_E - \text{heat source.}$$

Thus, the major energy loss channel, i.e., thermo-conduction, can be eliminated with this absorbing wall boundary condition (S. Krasheninnikov, PFSC at MIT, now at UCSD).

In non-recycling regime $\frac{5}{2}\Gamma T - S(\kappa_T \nabla T + \kappa_n \nabla n) = \int_0^r P dv$



DENSITY profile (left) is predetermined by the central fueling.

TEMPERATURE profile (right) adjusts itself in order to ELIMINATE the thermo-conduction.

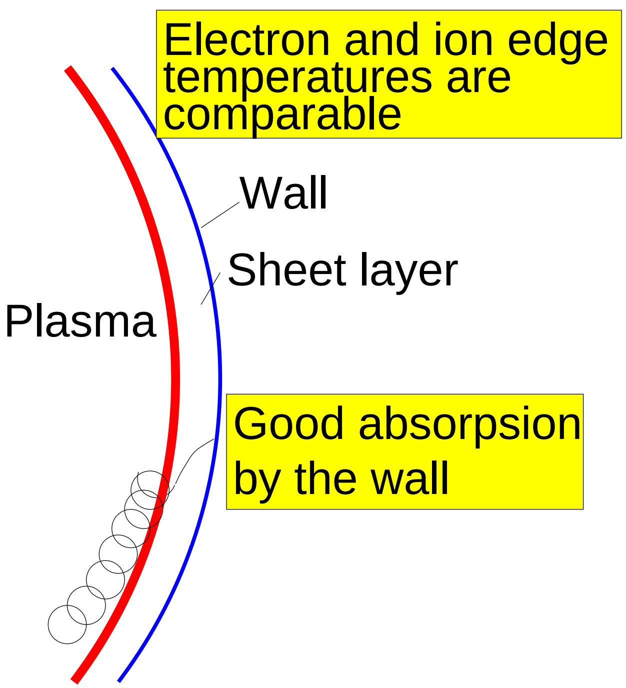
PRESSURE profile (left) has a jump at the plasma boundary.

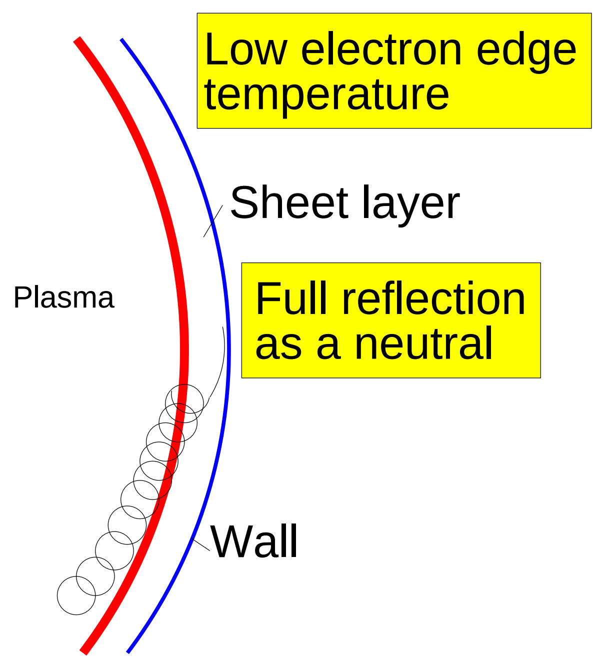
TEMPERATURE profile (right) eliminates the thermo-conduction irrespective to the heat source profile.

Crucial issues:

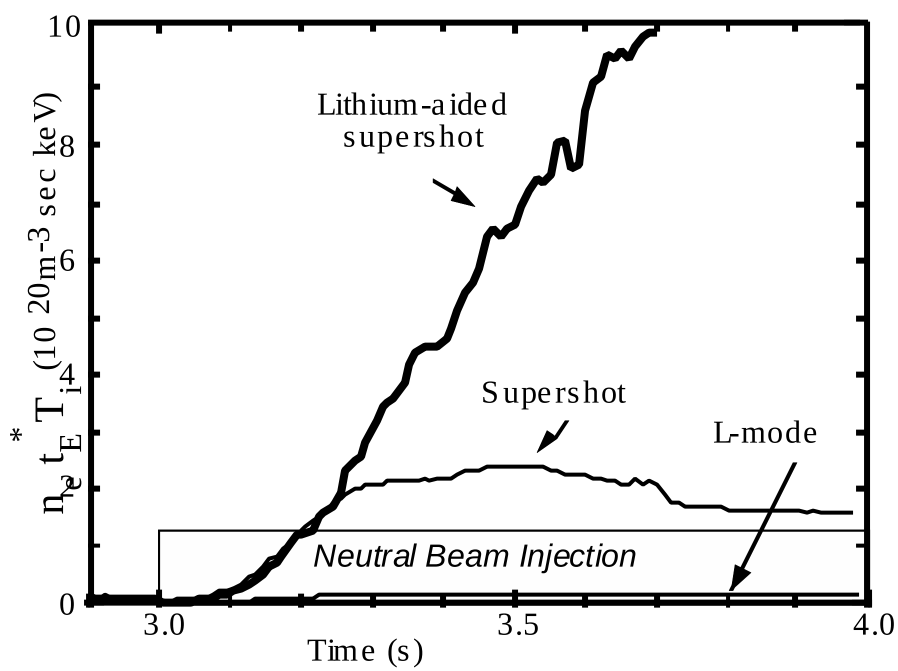
- Properties of lithium. For solid Li they are very attractive, e.g., 1 keV D-ion penetrates hundreds of monlayers of lithium (D.Ruzic, UL).
- Sheet potential near the walls. Is determined by the electron energy, $E \simeq 3T_e/\rho_i$.

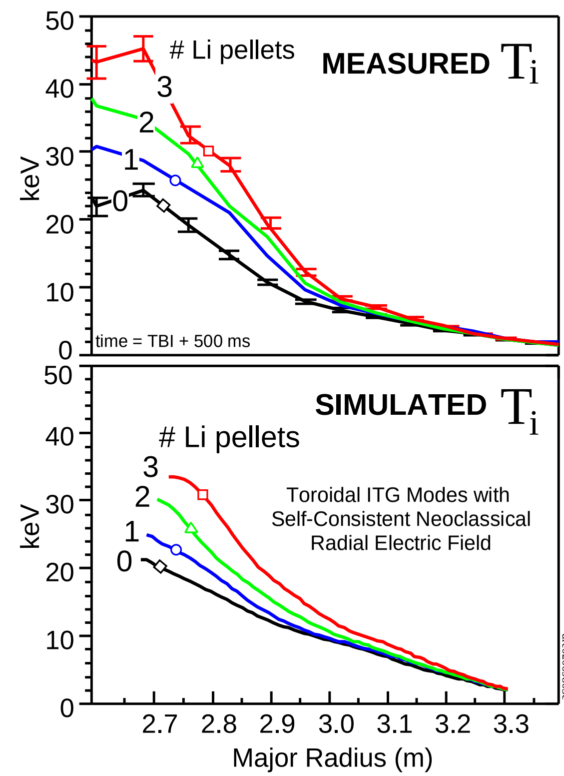
  Electrons in tokamaks are capable of giving unpleasant surprises.
- . . .





TFTR discovered and demonstrated that Lithium conditioning was the most important factor in its performance

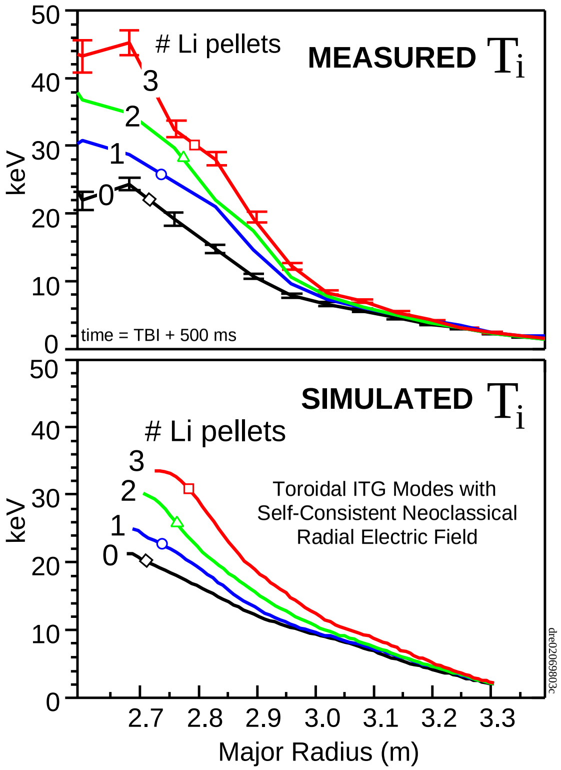


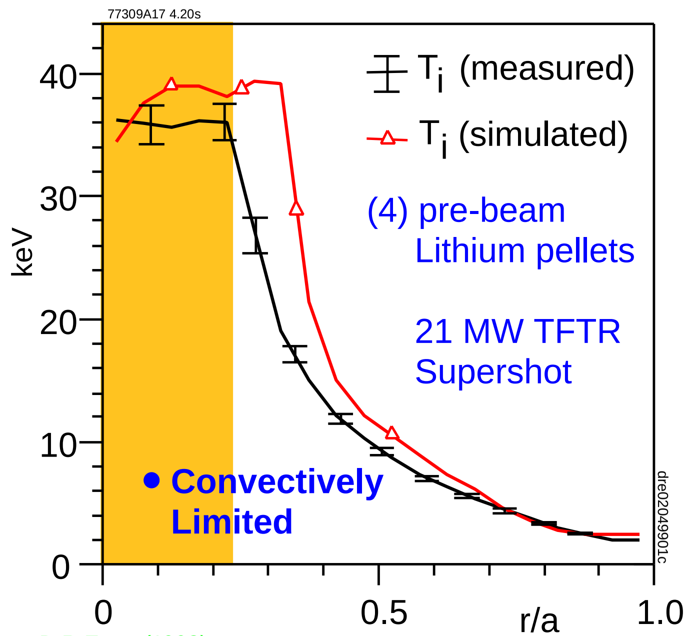


(TFTR # 83546 D.Mansfield, C.Skinner)

The increase in performance with increase in amount of lithium at the plasma edge has never been saturated.

Li Walls concept deffers in details from TFTR results but is consisitent in basic tendencies to flat the temperature in the core by reducing recycling at the edge

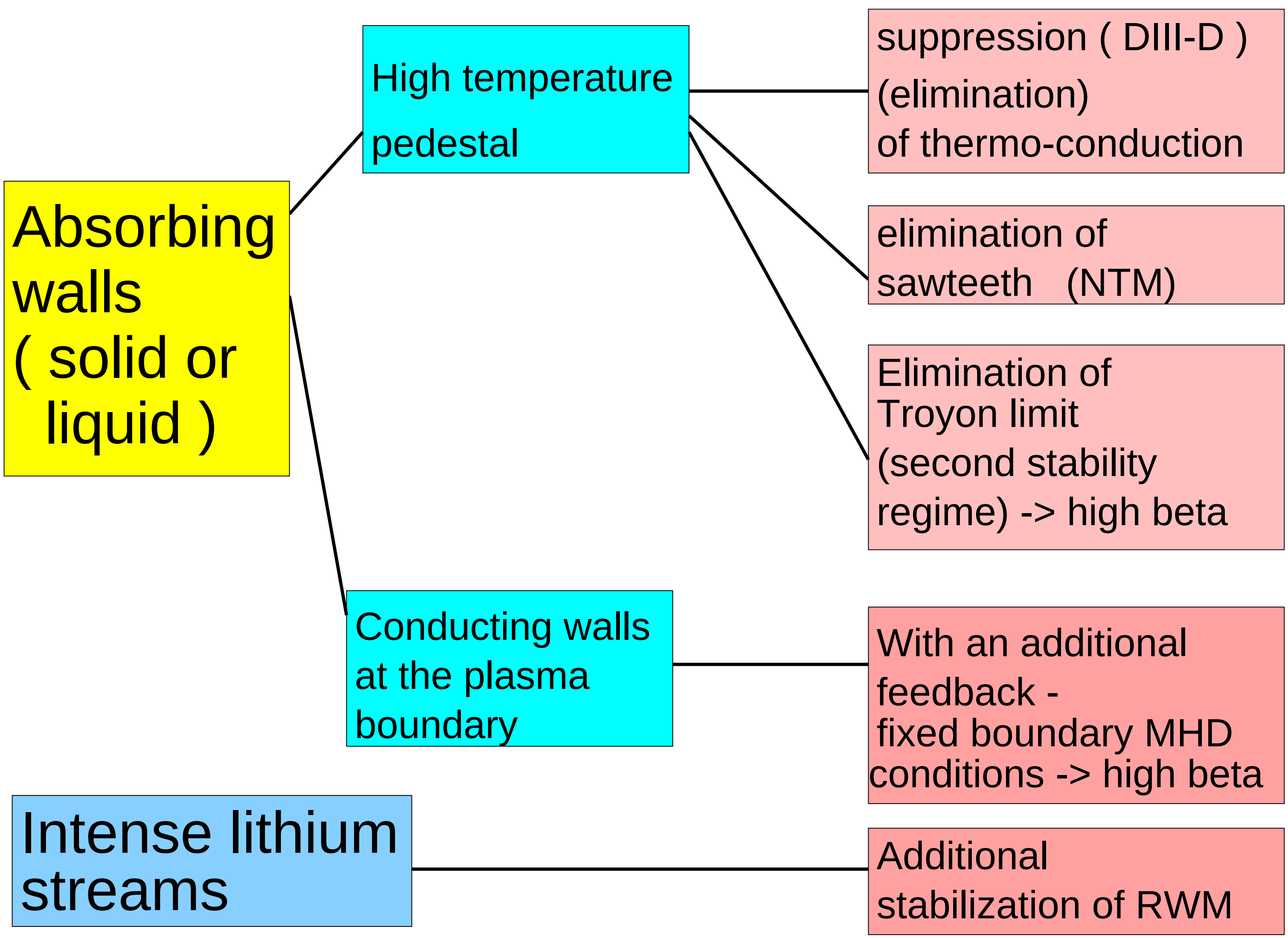




D.R.Ernst (1998)
J. D. Strachan, et al., EPS Inv. (1994).

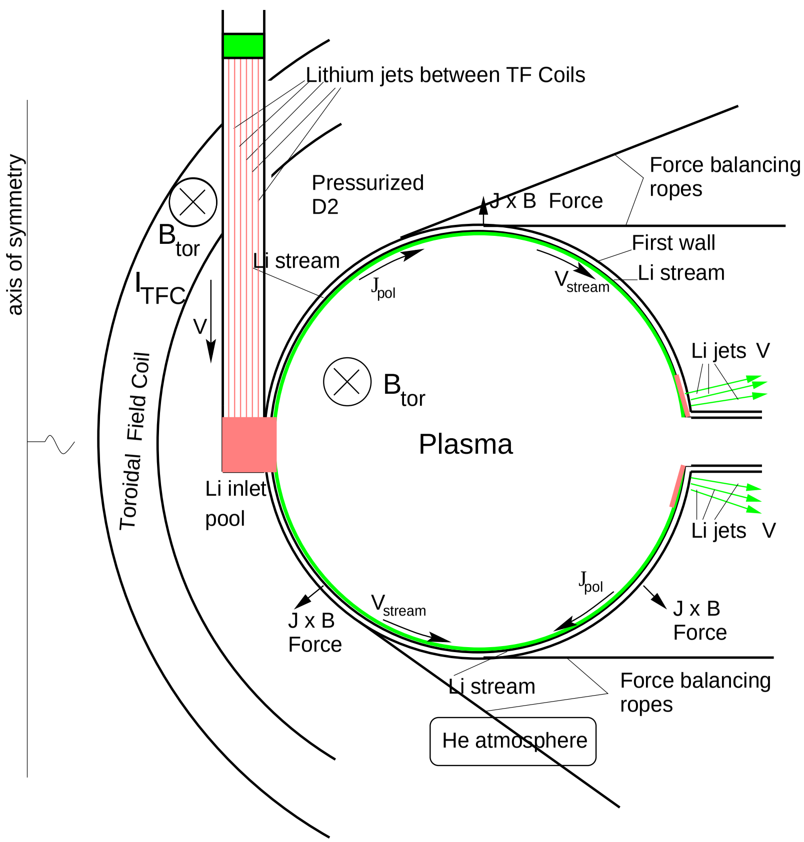
Goto K.Burrell (DIII-D, GA, CA) talk at APS-2000.

Lithium covered walls affect the very fundamentals of tokamaks



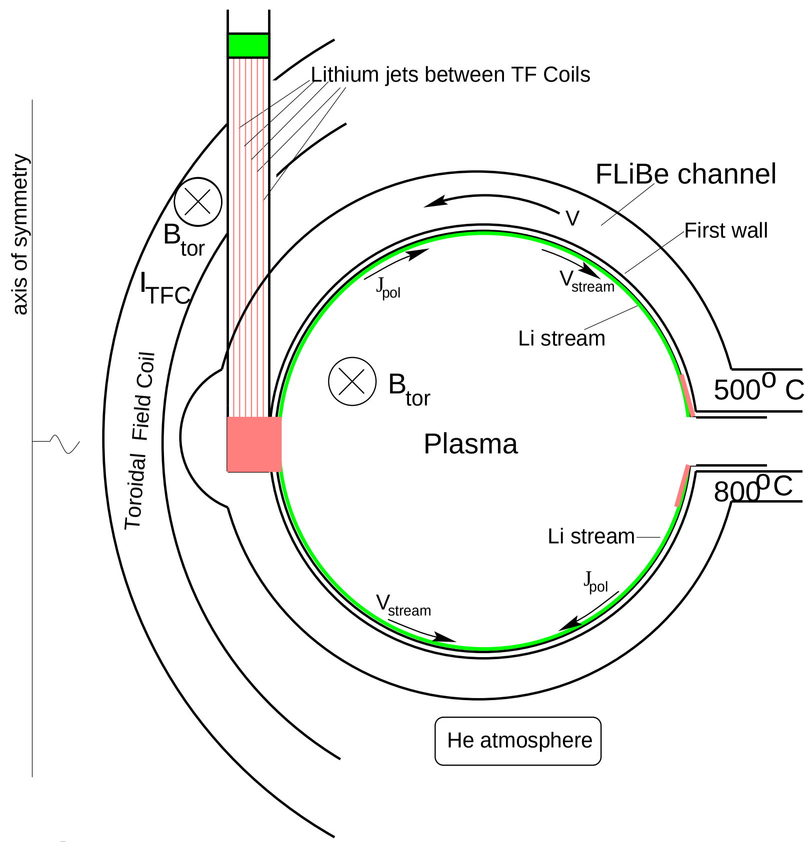
Intense Li Streams affect the very fundamentals of tokamak reactor desing.

Electrodynamic pressure creates a stable situation for the first wall.



- Guide wall works against expansion $\Longrightarrow$
- Guide wall can be made as a thin shell (like a car tire).
- Toroidal component of the electro-magnetic force can be balanced by the set of external wire ropes.
- Inner surface is sealed by the lithium streams (insensitive to cracks) $\Longrightarrow$
- Vacuum barrier can be moved to the plasma boundary (giving access to the neutron zone).

Intense lithium streams + FLiBe make an excellent FW/blanket combination (S.Zinkle, B.Nelson, ORNL)



Lithium streams keep the wall temperature below melting point of FLiBe

$$\boxed{T_{wall} \simeq 200^o - 250^0 < T_{melt,FLiBe} \simeq 450^o}$$

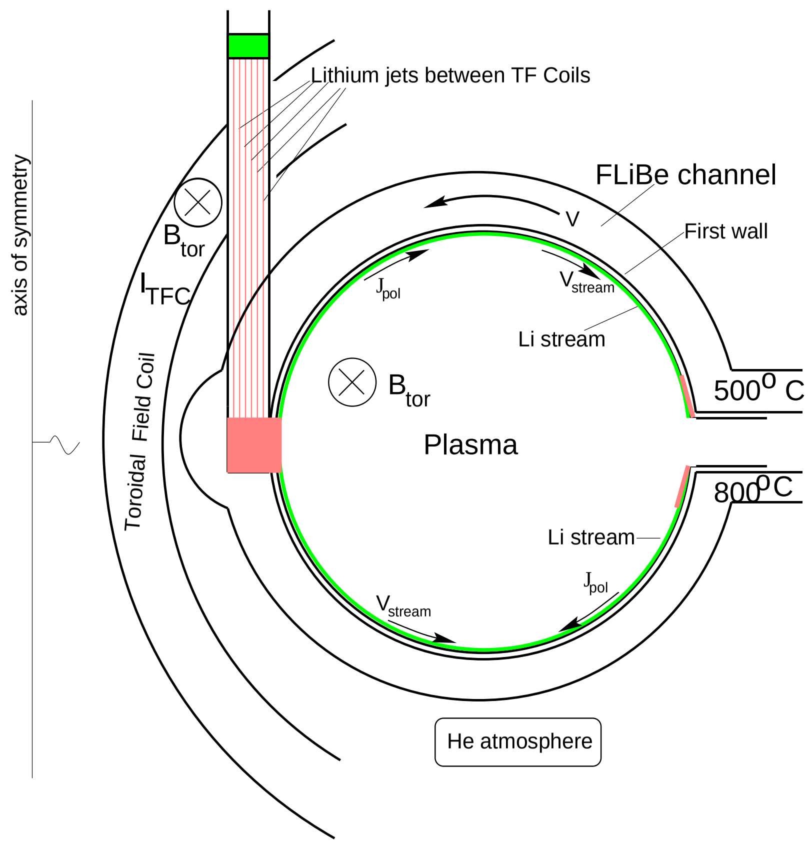
Independent of inner temperature in the chanell FLiBe has a solid boundary layer at the walls.

Even with $\boxed{T_{FLiBe}|_{outlet} = 800^o\ C}$ energy losses on the side walls are $\simeq 4\%$.

FLiBe

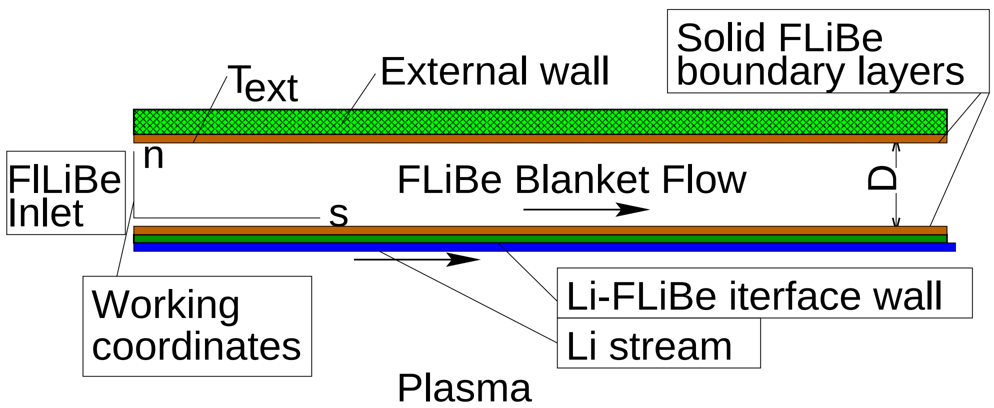
$$(LiF)_n(BeF_2)$$

It would be not crazy to think about making the vacuum chamber from the wire mesh



- wall becomes insensitive to thermal deformations $\Longrightarrow$ pulsed regime is acceptable (no high-tech for the current drive);
- deformations of the wall can be corrected on the fly (Yacht sail approach);
- wire wall presumably can withstand high neutron flux;
- minimum activation in the neutron zone;
- protection of feedback plates by the FLiBe layer with still excellent coupling with the plasma;

Stratified geometry of the FLiBe Blanket/Lithium streams



D	m	0.1
L	m	10
V	$\frac{m}{sec}$	0.5
$S(n)$	$\frac{W}{cm^3}$	100-40
$T_{side\ wall}$	C^o	200

The radial thickness D of the channel is assumed to be much smaller than the length L of the channel. Plasma side wall temperature is kept constant by a fast Lithium flow.

Heat source S corresponds approximately to 10 MW/m^2 in neutrons.

The walls of the channel are kept below the melting point of FLiBe, so two solid salt layers are formed on the walls of the channel.
The stationary heat diffusion equation

$$\begin{aligned} &\rho c_p V \frac{\partial T}{\partial s} = \kappa T''_{nn} + S, \quad T > T_{melt}, \\ &0 = \kappa T''_{nn} + S, \quad T < T_{melt} \end{aligned} \tag{5.1}$$

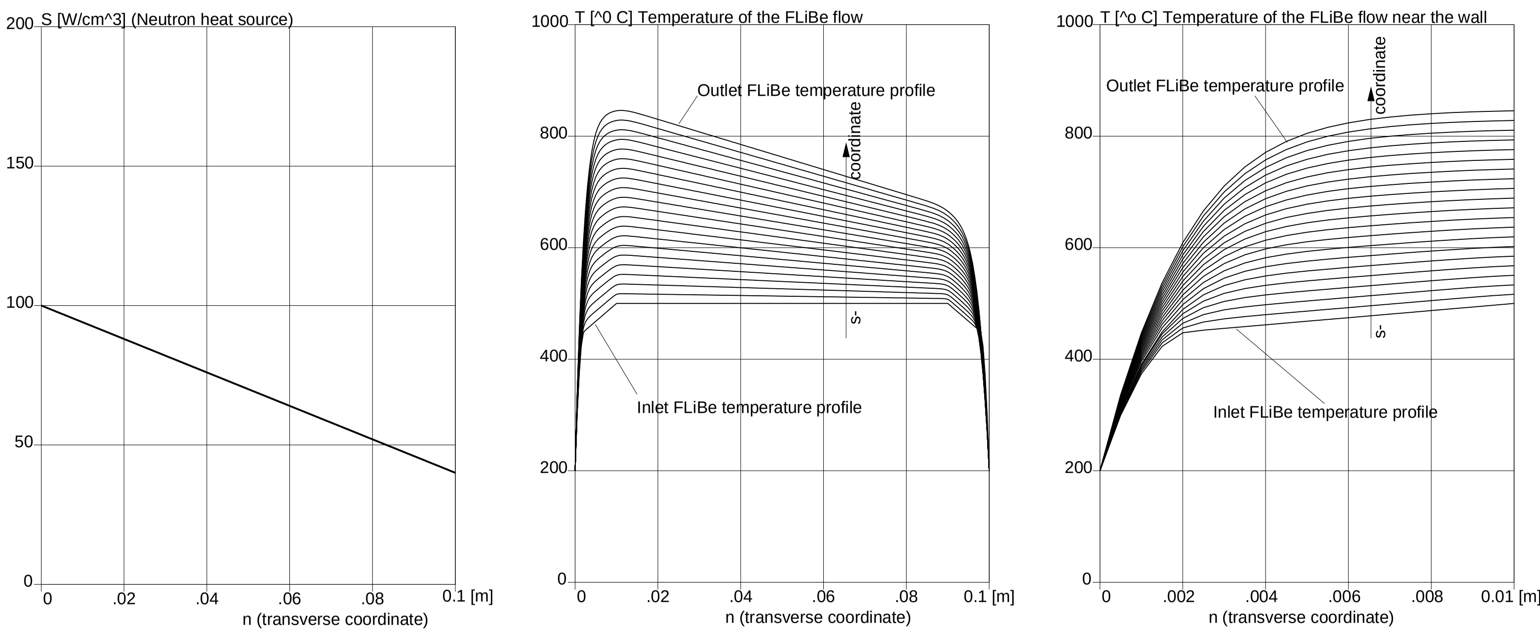
together with the matching conditions determines the temperature distribution in the flow.

Here, ρ is the mass density of FLiBe, c_p is the heat capacity, V is the velocity of the flow, κ is the thermo-conduction.

Thickness of the solid layer is determined as an eigenvalue of the problem in a self-consistent way.

FLiBe parameters		
ρ	$\frac{kg}{m^3}$	2240
c_p	$\frac{J}{kg \cdot C^o}$	2380
κ	$\frac{W}{m \cdot C^o}$	1
T_{melt}	C^o	450

Profiles of the (neutron) heat source and T in the FLiBe channel



FLiBe thermo-conduction is so small that the temperature inside body of the flow is determined solely by the heat source power

$$\rho c_p V \frac{\partial T}{\partial s} \simeq S, \quad T > T_{melt}, \tag{5.2}$$

not by thermo-conduction losses.

Two boundary layers of the order of 1-3 mm are formed near walls of the channel. Inside, each of them contains a sublayer of a solid FLiBe.

In the example the averaged energy losses are $0.26\ MW/m^2$ through the plasma side wall and $0.16\ MW/m^2$ through the Toroidal Field Coil (TFC) side of the wall, which constitute approximately 4 % of the incoming neutron flux energy.

FLiBe seems to be a perfect coolant for the tokamak-reactor

Yacht Sail approach for the fusion reactor:

Liquid FLiBe Blanket

Intense Li plasma facing streams

Dynamically balanced thin vacuum chamber wall

low pressure and minimal ammount of activated structures in the neutron zone

high temperature of the reactor coolant

insensitivity to thermal deformations

Inductive current drive is acceptable

best envirionement for feedback RWM stabilizing coils (behind the FLiBe layer)

Additional stabilization of RWM by lithium streams

6 Summary

From the very first presentation to PPPL (PS&T seminar, Jan. 08, 1999), the idea of a tokamak with lithium covered walls was presented as a consistent tokamak-rector concept.

For the first time, the renewable and absorbing plasma facing walls were introduced into the tokamak research.

From the plasma physics side, lithium walls may provide

- a low recycling regime (best possible for energy confinement);
- low-Z plasma facing surface (with a central plasma fueling and surface impurities source);
- rector relevant power extraction capabilities from the plasma
- wall conditions, which are not sensitive to the edge plasma temperature as soon as it exceeds a certain level (about 1 keV).
- slowing down free-boundary MHD instabilities,
- etc,

Li Walls, for the first time, introduce the "Yacht Sail" approach for the fusion reactor design, which may provide

- insensitivity of the structure to thermal/electro-magnetic perturbation;
- best environment for both internal and external plasma stability control;
- elimination of (unrealistic) requirement for the stationary regime;
- efficient power extraction from the neutron zone with a high temperature (FLiBe) coolant;
- minimizing the content of activated structural elements;
- simplification of the entire reactor control and maintainence scheme
- . . .

7 Does the tokamak fusion have a path ?

Go to netscape

Inside the fusion, we, fusion physicists, should, first, realize the deep meaning of what Sean Connery said about the tokamak fusion

"It is impossible *(in the conventional way, LZ)*",

". . . but doable *(if we follow the way of physics, LZ)*"

(S. Connery, TWENTIETH CENTURY FOX and REGENCY ENTERPRISES film "Entrapment", 1999)

You, our physics colleagues outside fusion, should always remind us to be on the right track in the great endeavor to make the tokamak working in our life time limit as a commercial power reactor.

Integrated approach to fusion reactor

Plasma science part

Solid Li

New plasma regime:

suppressed turbulence,
second stability,
resistive wall at the
plasma boundary, ...

Liquid Li

Technology opportunities:

for Plasma Facing Comp.,
power extraction,
liquid (FLiBe) blankets, ...

New schemes for the tokamak reactor:

reduced activation,
smaller size and Btor,
reduced reliance on
shaping and
high-tech plasma control
...